
“Micro”sats

Siegfried W. Janson

Center for Microtechnology,
The Aerospace Corporation
El Segundo, California (USA)

May 2000

Definitions

Logical:	Real World:
• Microsat: 1 kg to 100 kg	10 to 100 kg
• Nanosat: 1 gram to 1 kg	1 to 10 kg
• Picosat: 1 mgram to 1 gram	less than 1 kg
• Femtosat: 1 μ gram to 1 mgram	?????????????????

A “Microsat”
from the 1960's:



Static Inflation Test of 135 Ft Satellite In Weeksville, NC
NASA Langley Research Center

6/28/1961

Image # EL-1996-00052



Micro/Nanosatellite Series from the 1990's

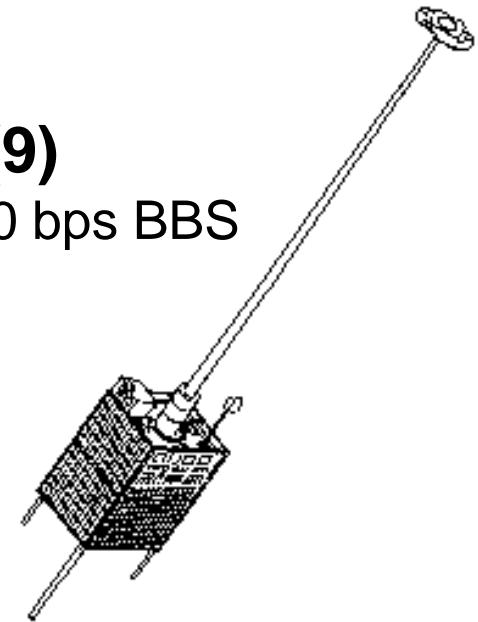
- AMSAT “Microsats” (6)**

- 10-kg mass, 23-cm cubes, VHF/UHF, 1200 bps store-and-forward
- Passive magnetic stabilization
- U.S., Argentina and Italy

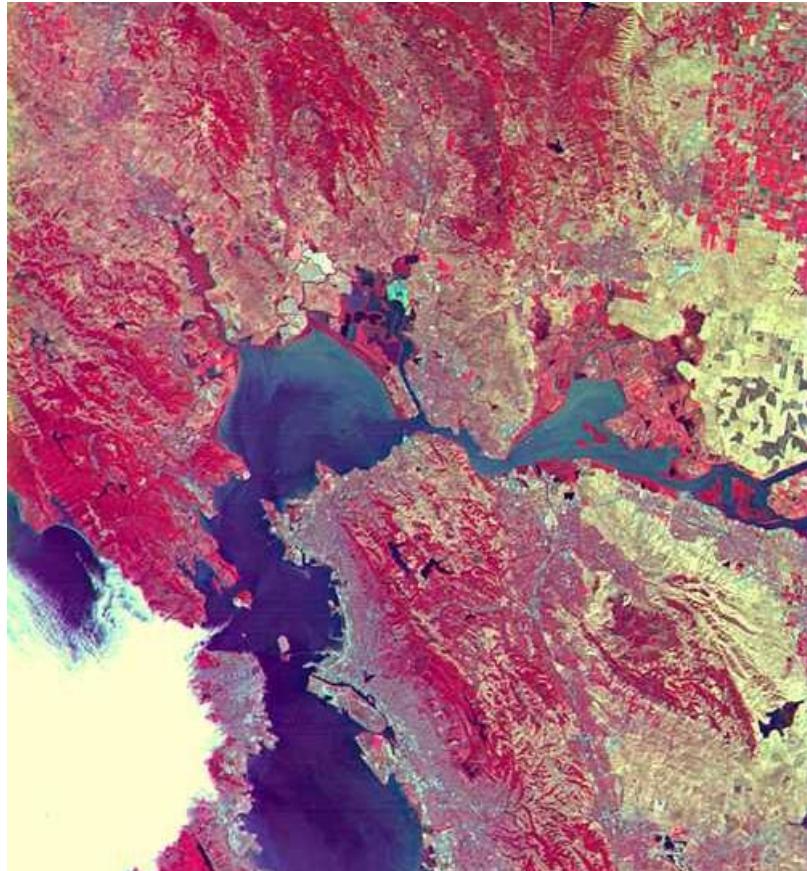
- Surrey Satellite Technology “Microsats” (9)**

- 50-kg mass, 35 x 35 x 60 cm box, VHF/UHF, 9600 bps BBS
- Gravity-gradient stabilization
- Low-resolution earth-imaging
- Sold to Korea, France, Portugal, and Thailand

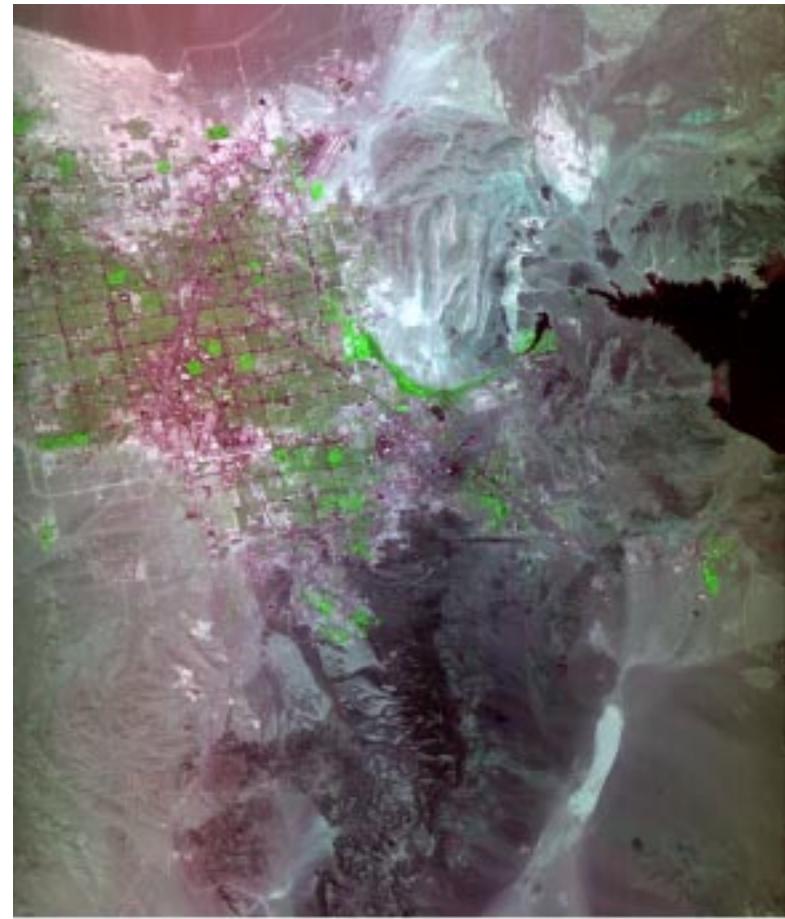
See: <http://www.amsat.org>
 <http://www.sstl.co.uk/default.htm>



Microsat Multi-Spectral Images



San Francisco at 98-meter resolution
http://www.sstl.co.uk/services/mm_san_fransisco.html



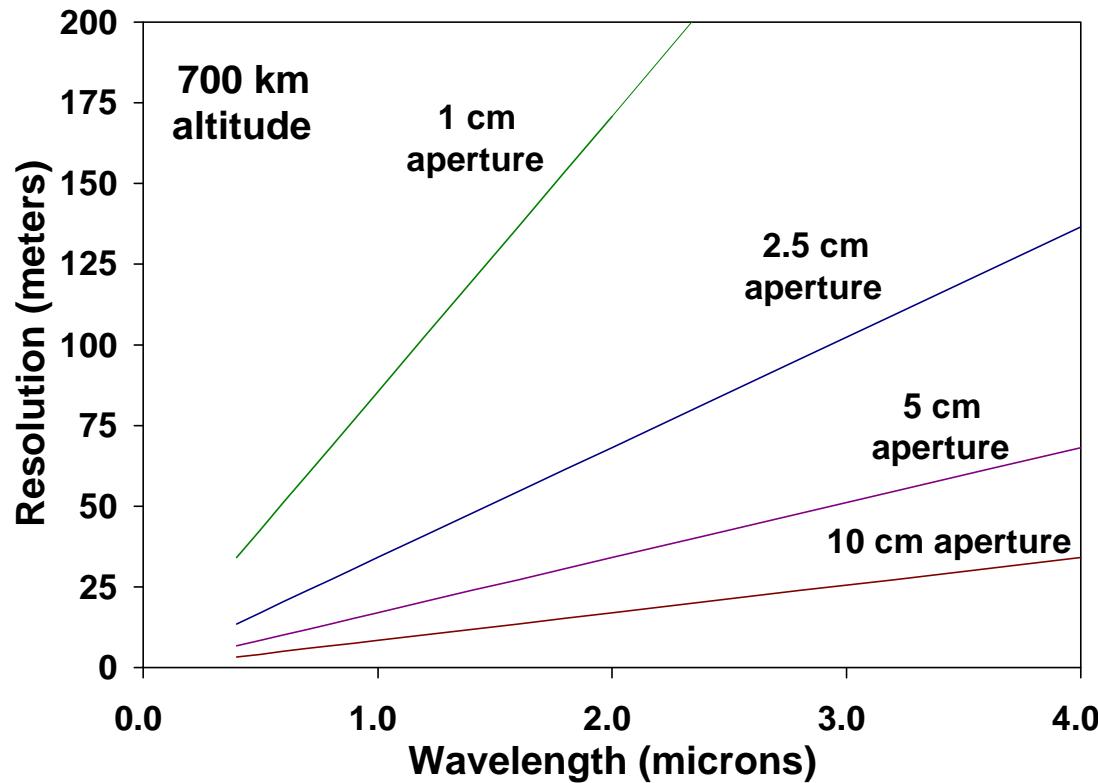
SaTReC 우리별 3호 (KITSAT-3)
한국과학기술원 원공위성연구센터

Las Vegas (USA)
99/06/11 20:02:03

Las Vegas at 15-meter resolution
http://krsc.kaist.ac.kr/english/k3_pict_990611.html

Ground resolution for Optical Micro/Nanosats:

Diffraction-Limited Resolution:

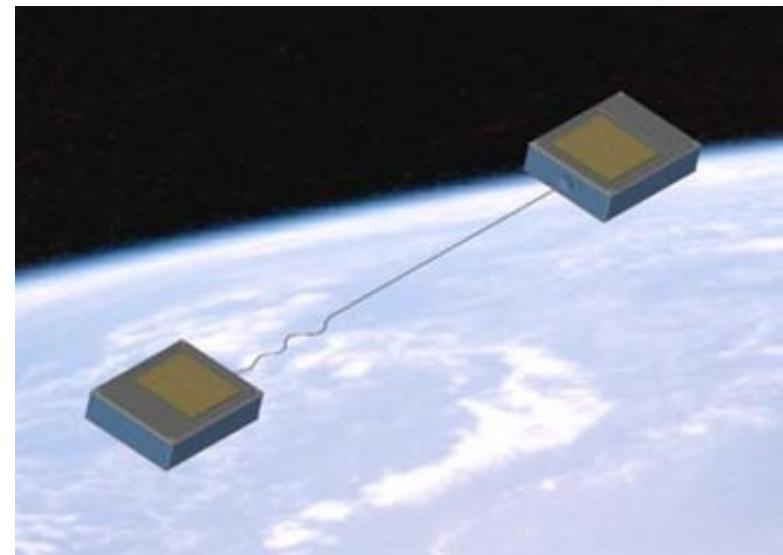


DARPA/Aerospace PICOSATS



The Aerospace Corporation

4" x 3" x 1" each



The Aerospace Corporation

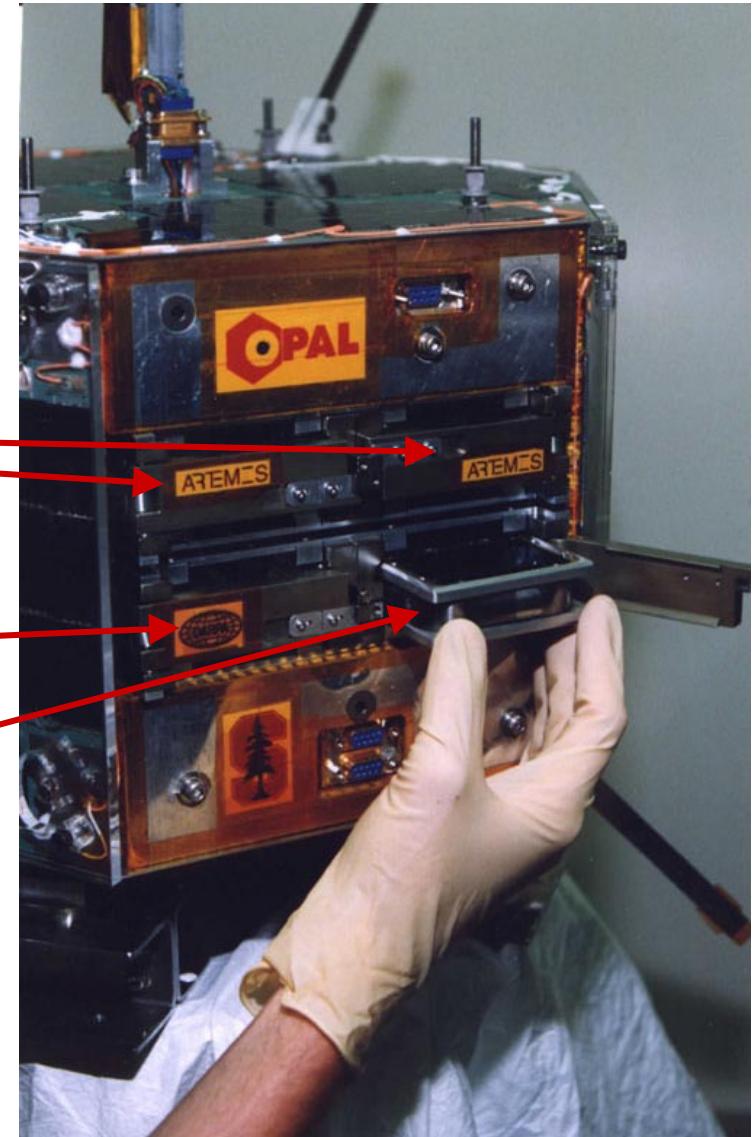
**On-Orbit Configuration
with 100 foot tether**

Loading Picosats into Stanford's OPAL Microsat

Double-length PICOS
(Thelma and Louise)

Aerospace/DARPA PICOS

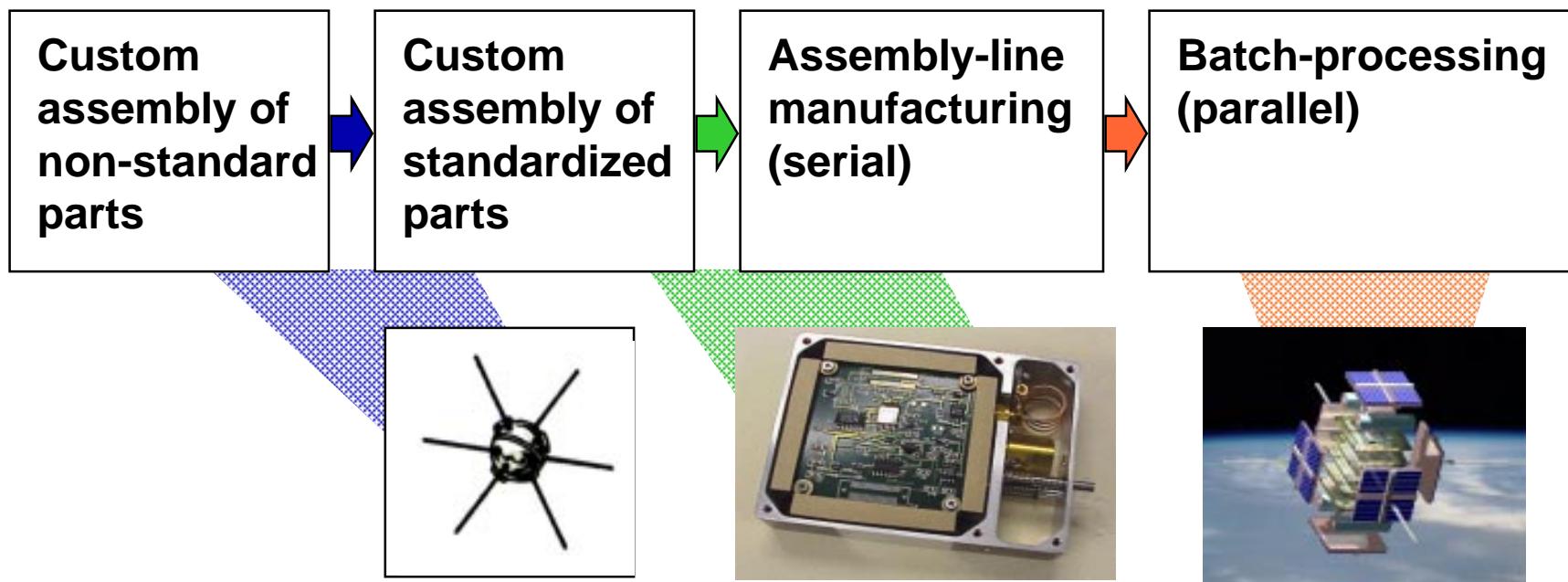
Stensat and JAK



[http://ssdl.stanford.edu/opal/PhotoGallery/
StanfordPicoLoading/StensatInLauncherTubeWithHand.html](http://ssdl.stanford.edu/opal/PhotoGallery/StanfordPicoLoading/StensatInLauncherTubeWithHand.html)

A “Micro” Revolution for Spacecraft

The Evolution of Manufacturing:



Small Spacecraft:

Launch Year:

Functional Elements:

Vanguard 1

1958

~100

DARPA PICOSAT

1999

~100,000

“Integrated” Satellites

~2005

~100,000,000

Microelectronics: The Evolution of a Revolution

Year:	Smallest Feature (microns)	Dynamic RAM:		Microprocessors:	
	Die Size (cm ²)	Billions of Bits per Dice	Die Size (cm ²)	Millions of Transistors per cm ²	
1995	0.35	1.9	0.064	2.5	4
1998	0.25	2.8	0.256	3.0	7
2001	0.18	4.2	1	3.6	13
2004	0.13	6.4	4	4.3	25
2007	0.10	9.6	16	5.2	50
2010	0.07	14	64	6.2	90

The microelectronics “revolution” continues along a predictable path

From “Technology 1996: Solid State”, *IEEE Spectrum*, 33 #1, p. 51-55, January 1996

Command and Data Handling

Galileo on-board computer:

0.5 MIPS throughput, 50 W power, 125 kiloword memory

AMSAT microsat on-board computer: (1990 technology)

V- 40 (AT-class PC) CPU with 4 megaword memory

1 MIPS throughput at 0.45 W with 9.83 MHz clock

Single chip microcontroller example: (1994 technology)

PIC16C57 series microcontroller by Microchip:

2K x 12 EPROM, 80 byte RAM, 20 I/O lines, 8 bit clock

40 kHz clock: 4 KIPS throughput at 15 mW power

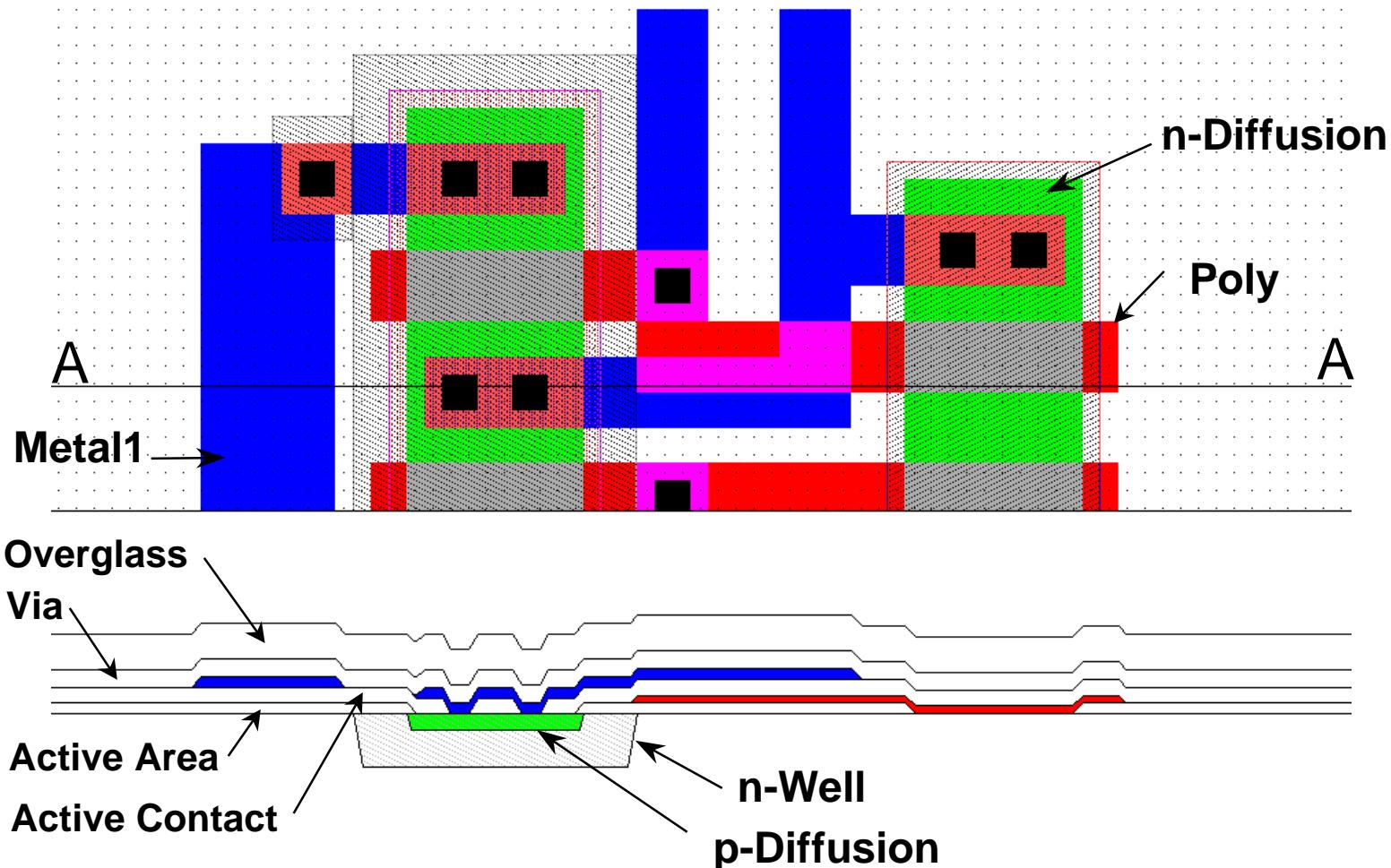
20 MHz clock: 2 MIPS throughput at 100 mW power

AMSAT P3D computer: (1997 technology)

Strong ARM CPU with 8 megabyte memory

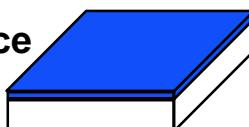
130 MIPS throughput at 1.5 W (entire C&DH unit)

NAND Gate Cross-Section:

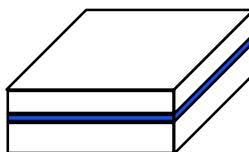


BASIC MICROFABRICATION STEPS

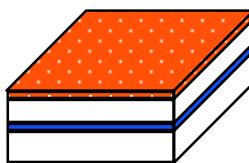
1. Dope silicon to produce a stop-etch layer



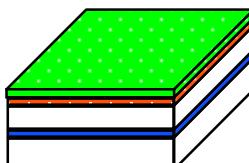
2. Add new polysilicon layer



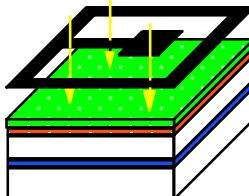
3. Grow oxide layer



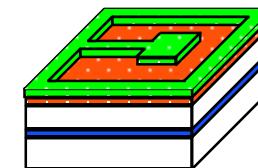
4. Add photoresist layer



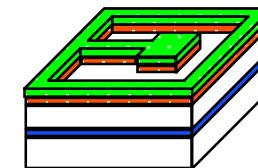
5. Expose through mask



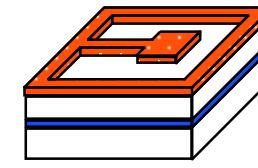
6. Develop photoresist



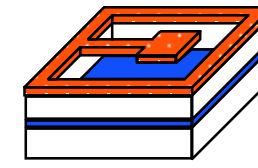
7. Etch through oxide



8. Remove photoresist



9. Etch silicon down to etch stop layer

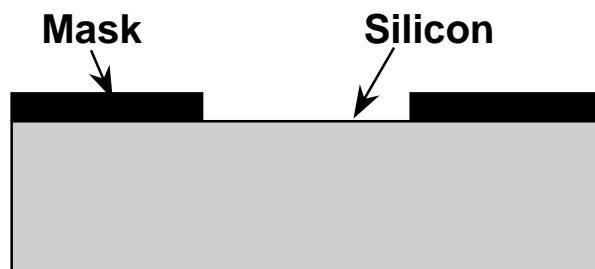


Surface Micromachining:

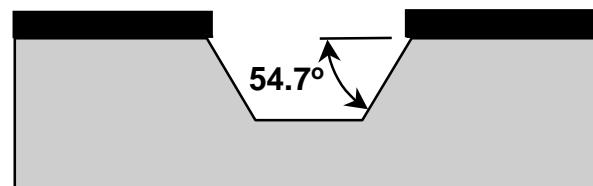
Structural Layer	Sacrificial Layer
Polysilicon	Silicon Dioxide (glass)
Silicon Nitride	Silicon Dioxide (glass)
Silicon Dioxide	Polysilicon
Tungsten	Silicon Dioxide (glass)
Molybdenum	Aluminum
Silicon Carbide	Silicon Dioxide (glass)
Shape Memory Alloy (TiNi)	Polyimide or Gold

Bulk Silicon Micromachining:

Unetched



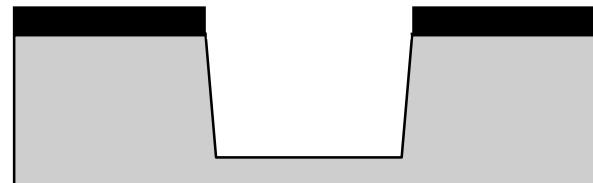
Wet Chemical Anisotropic Etch



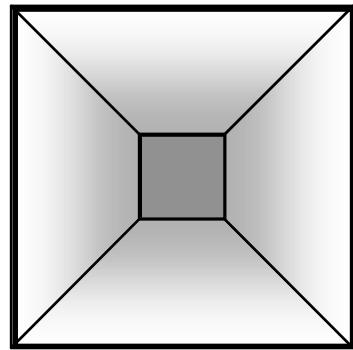
Wet Chemical Isotropic Etch



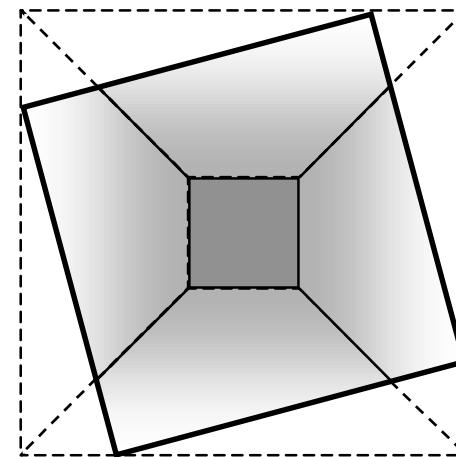
Reactive Ion Etch



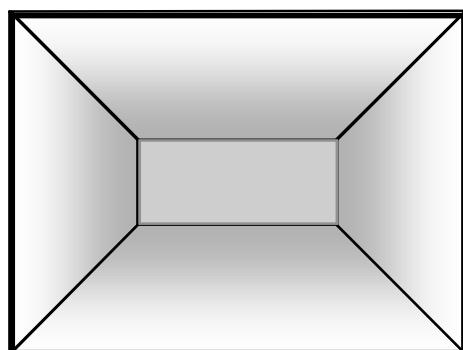
Anisotropic Etch Patterns in Silicon



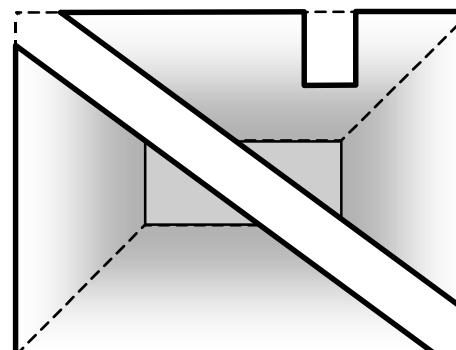
A



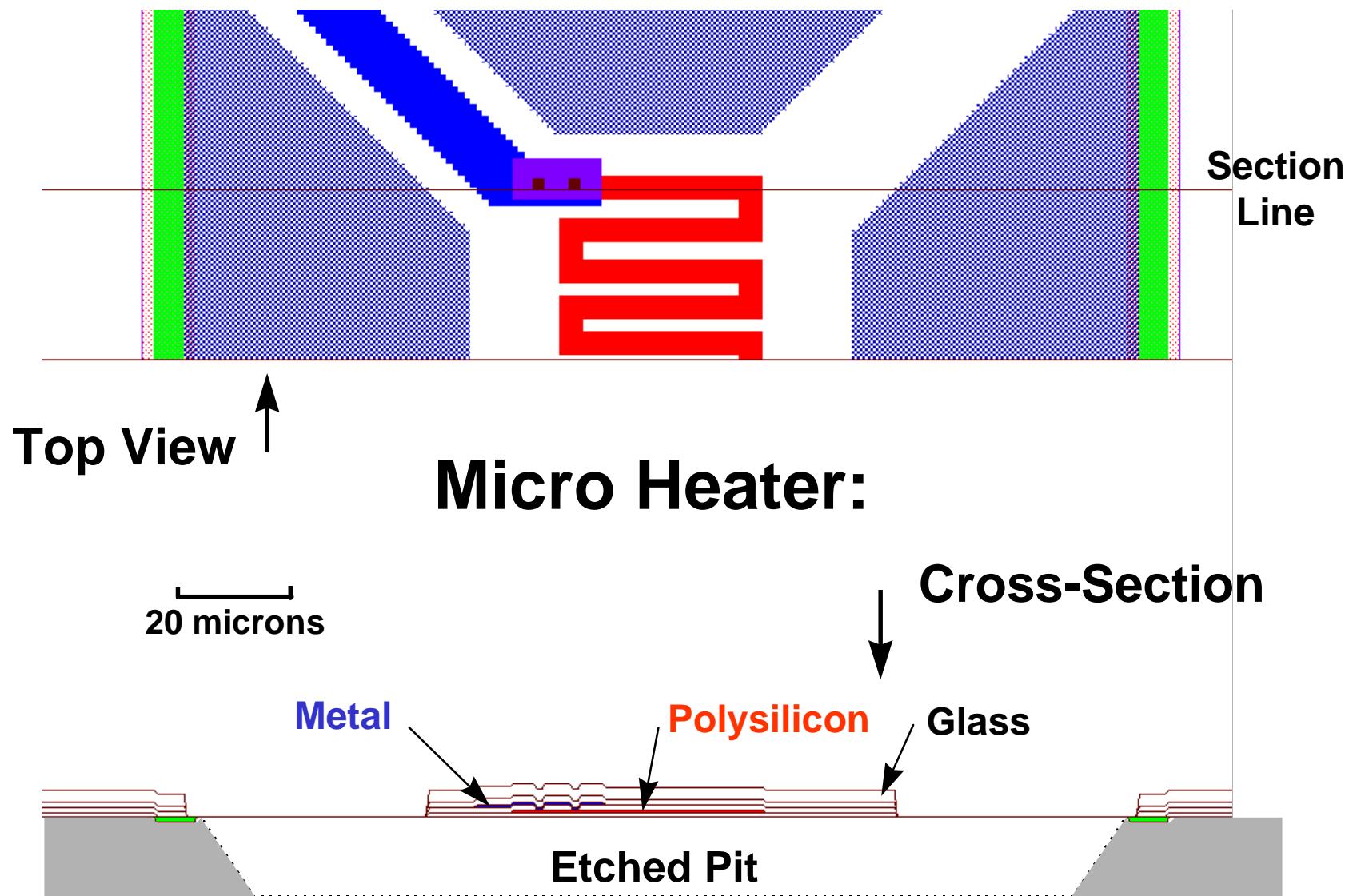
C



B

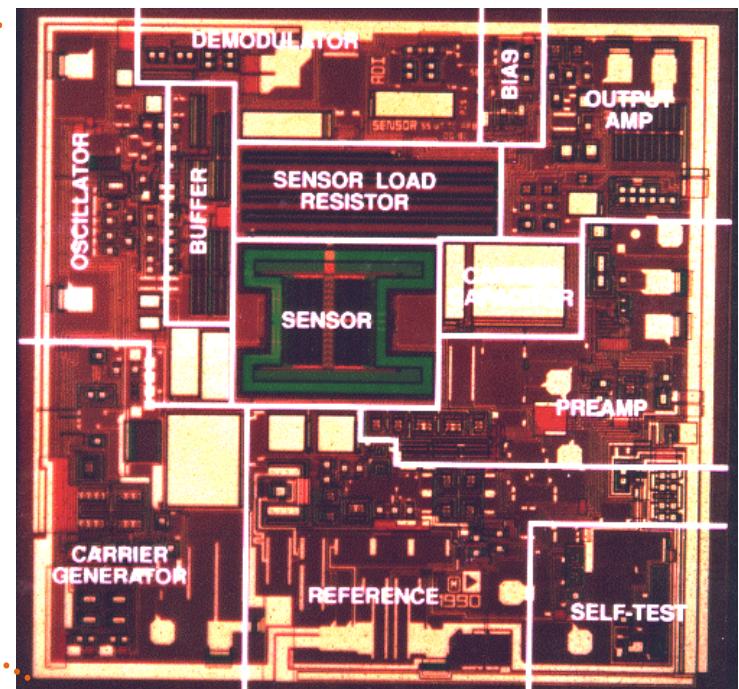
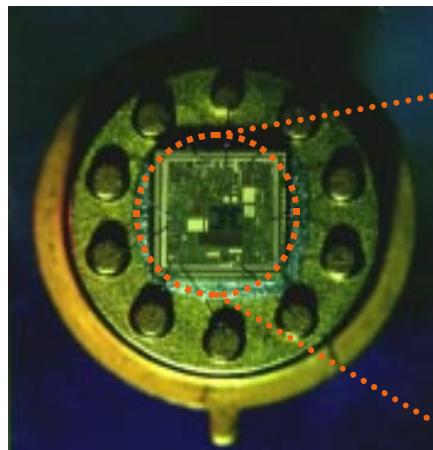


D

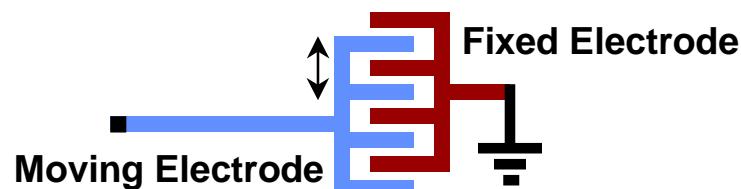


A REVOLUTION IN MECHANICAL CONSTRUCTION: MICROELECTROMECHANICAL SYSTEMS (MEMS)

Analog Devices ADXL50 Accelerometer

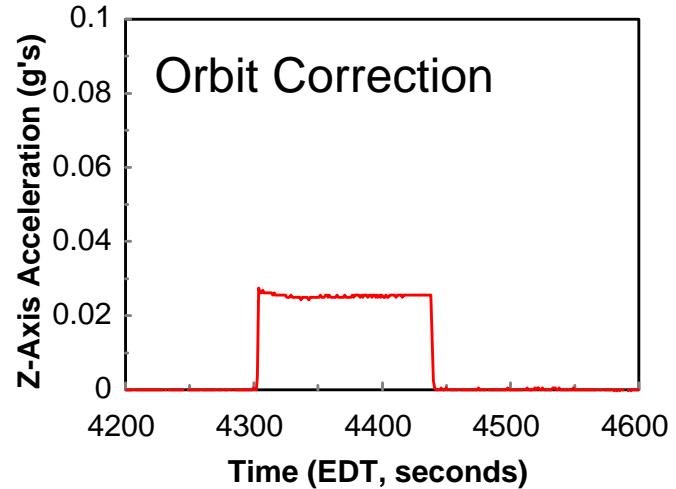
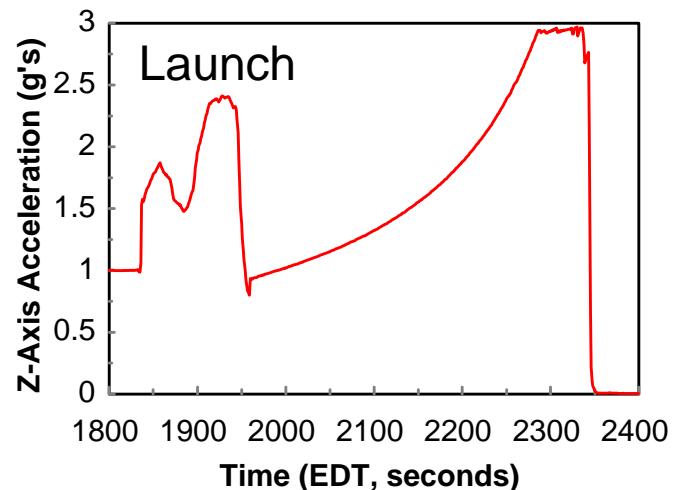
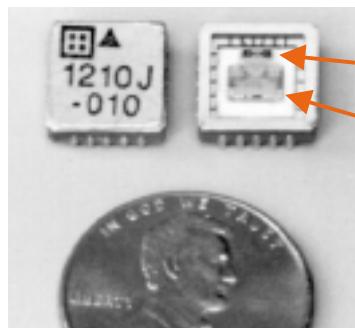
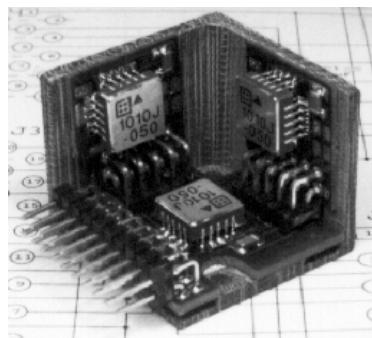


Principle of operation:



MEMS Accelerometers Monitored STS-93 Flight

Silicon Designs 1010J & 1210J
Capacitive MEMS Accelerometers



Why MEMS Are An Enabling Technology

- You can simultaneously fabricate thousands of devices
 - Micron-to-millimeter scale machines
 - Coordinated primitive functions by multiple devices can produce complex functions (like a computer!)
- Integrated electronics can be co-manufactured
 - Increased signal-to-noise ratios for sensors due to reduced parasitic loads
 - You can produce “smart” sensors and actuators for high reliability
- Reduced size and power requirements for sensors
- Traditional off-chip components can be made on-chip
 - High frequency inductors, bandpass filters, etc.

Possible MEMS Insertion Into Spacecraft Systems:

Command and Control Systems:

- “MEMtronics” for ultra-radiation-hard and temperature-insensitive logic

Inertial Guidance Systems:

- Microgyros and microaccelerometers
- Micromirrors and microoptics for fiber optic gyros

Attitude Determination and Control Systems:

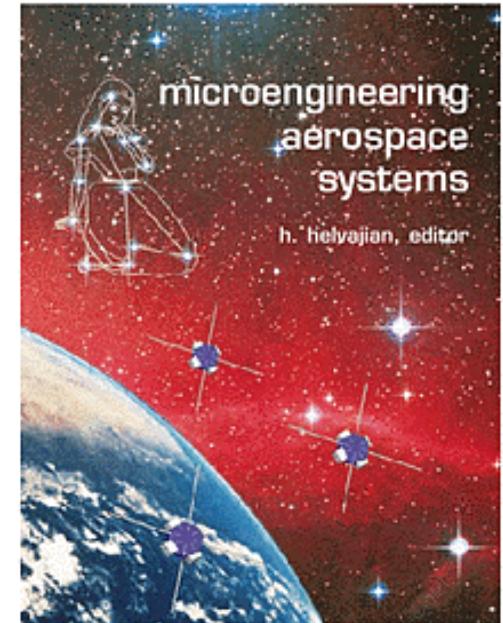
- Micromachined sun and Earth sensors
- Micromachined magnetometers

Propulsion Systems:

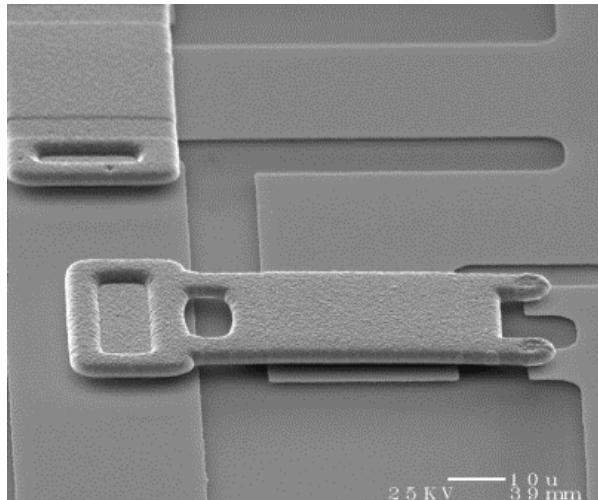
- Micromachined pressure and chemical sensors
- Arrays of single-shot thrusters (“digital propulsion”)
- Continuous or pulsed microthrusters

Communications and Radar Systems:

- Very high bandwidth, low power, low resistance rf switches
- Micromirrors and microoptics for laser communications

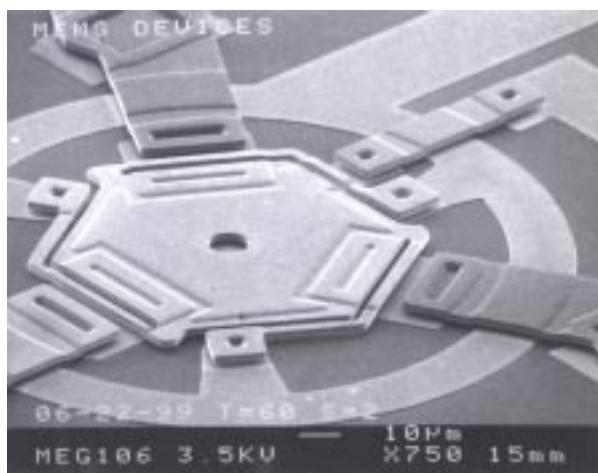


MEMS Switches: RF, Digital, or Analog



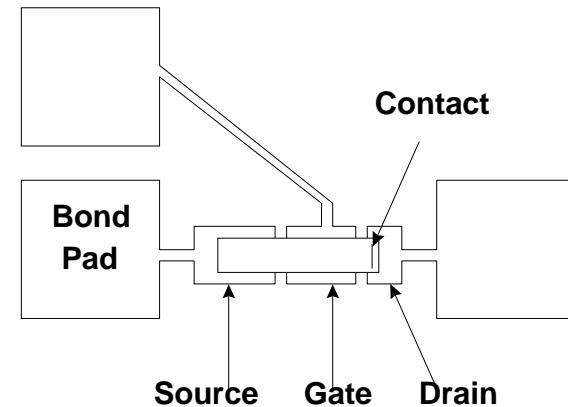
From:
P.M. Zavracky et al.,
“Micromechanical Switches
Fabricated Using Nickel
Surface Micromachining,” *J.
Microelectromechanical
Systems*, **6** #1, March 1997

<http://www.ece.neu.edu/edsnu/zavracky/mfl/programs/relay/relay.html>



From:
Aerospace Corp.

Top View:



Side View:

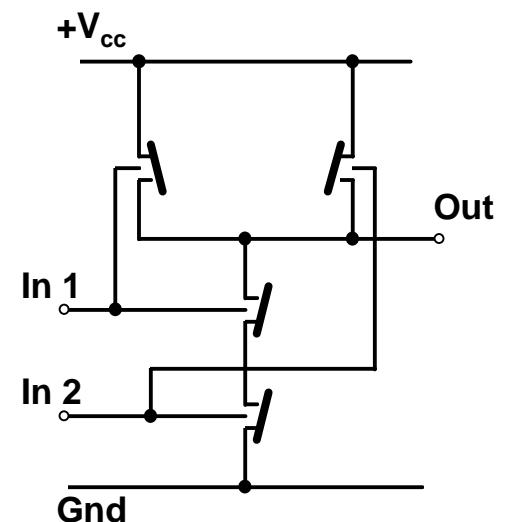
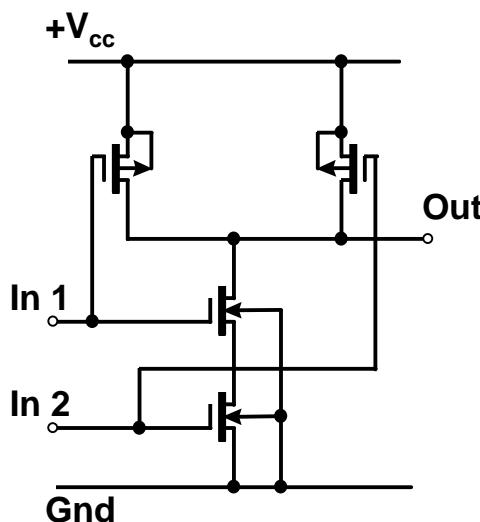
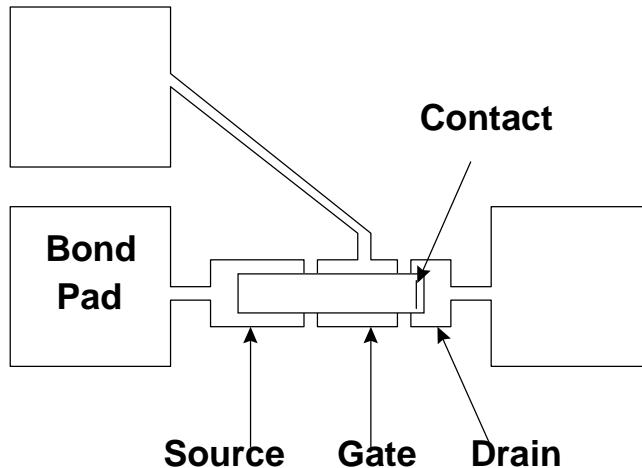


- ***Super radiation-hard,***
- ***Wide operating temperature range***
- ***Low insertion loss***
- ***Wide bandwidth***

“MEMtronics”

- *Super radiation-hard and wide operating temperature range*

Top View:



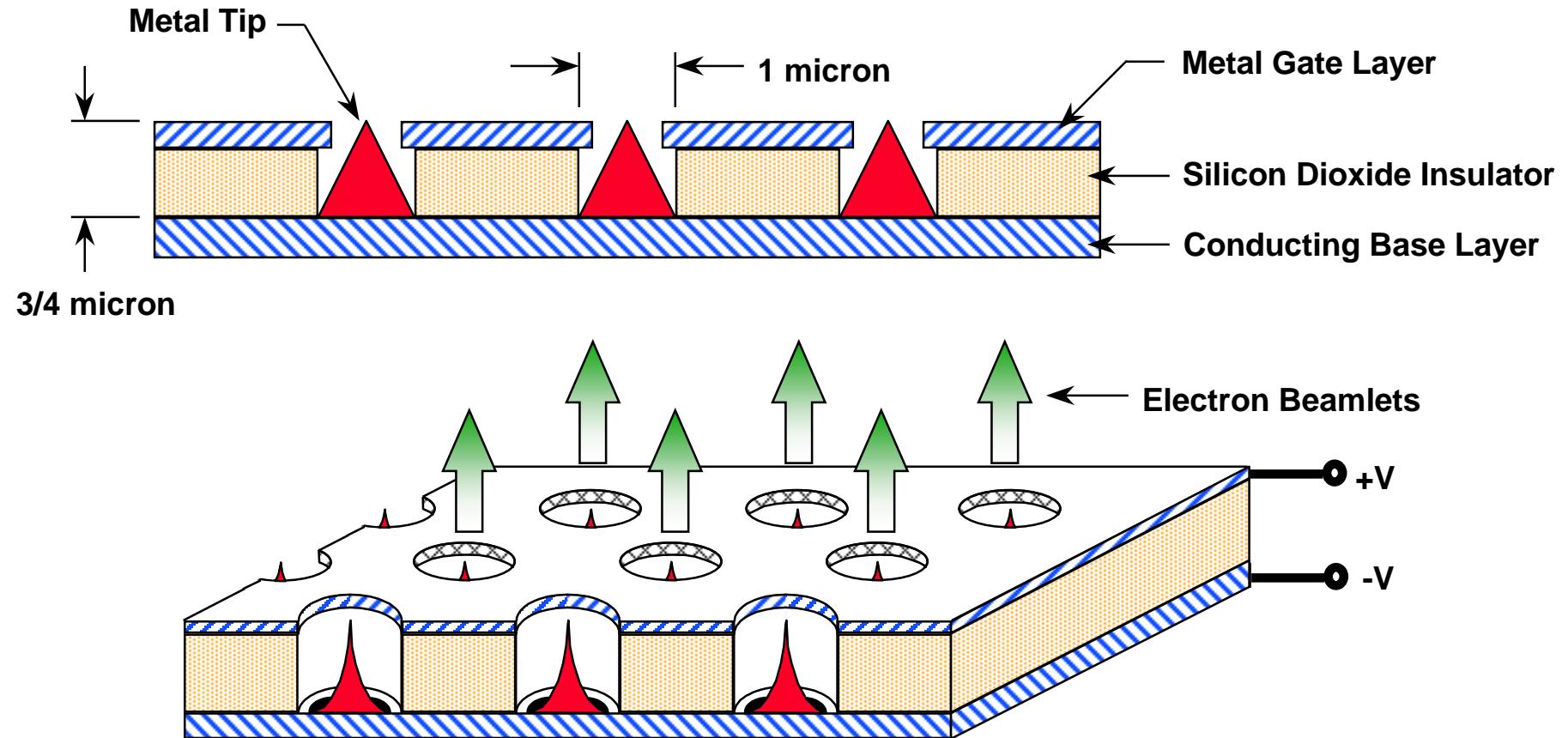
Side View:



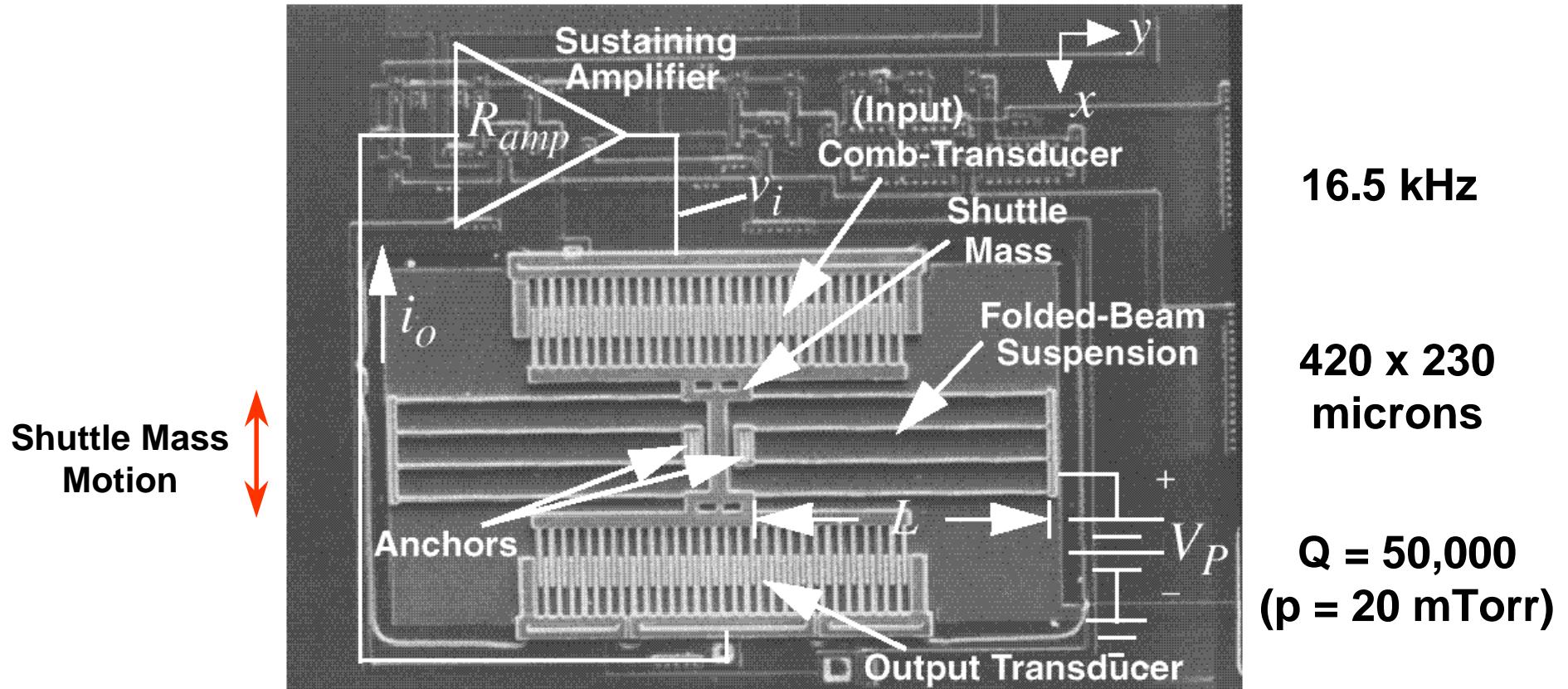
A. Electronic NAND gate

B. MEMtronic NAND gate

SPINDT CATHODES: Micromachined Cold Cathodes



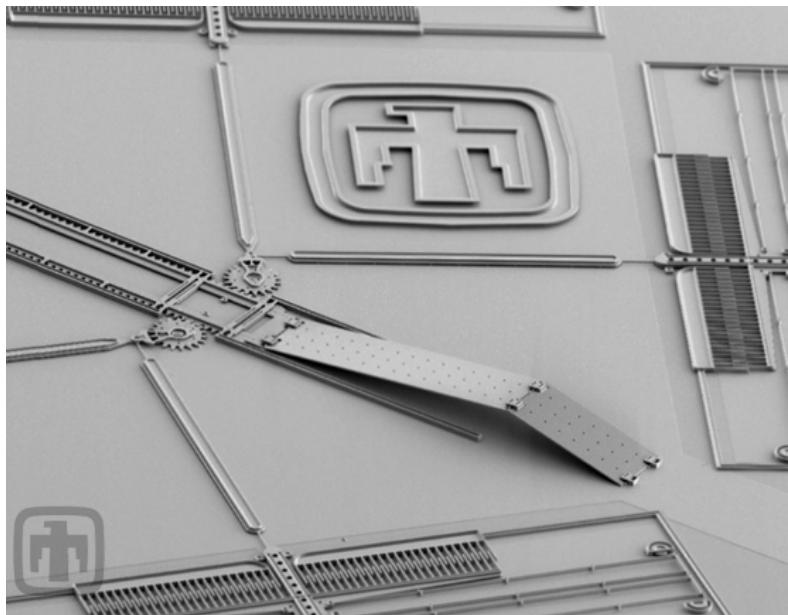
μ Mechanical CMOS Resonator Oscillator



From "Frequency-Selective MEMS for Miniaturized Communications Devices," by Clark T.-C. Nguyen, Proc. of the 1998 IEEE Aerospace Conf., Snowmass, CO, March 98

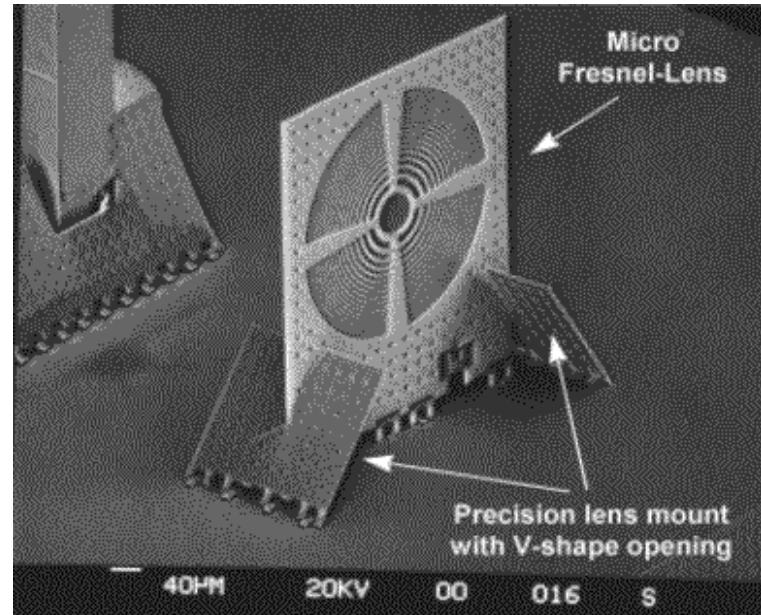
Optical MEMS Devices for Possible Space Applications

**MEMS “Pop Up” Mirror
(Sandia)**



[http://www.mdl.sandia.gov/micromachine/
images6.html](http://www.mdl.sandia.gov/micromachine/images6.html)

**MEMS “Pop Up” Lens
(UCLA)**

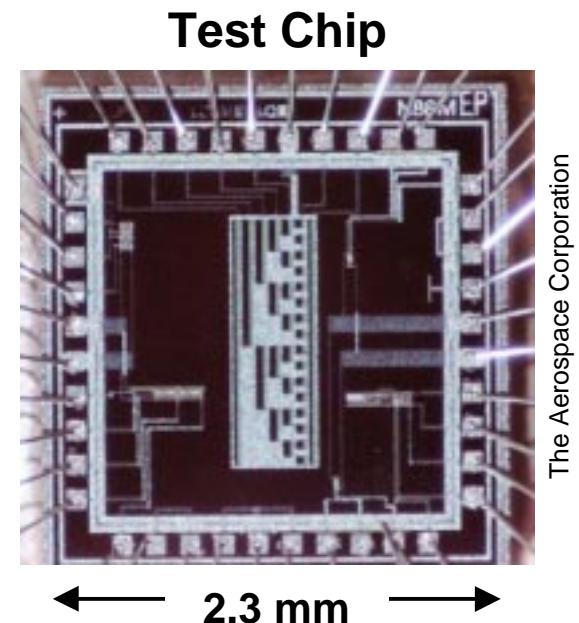
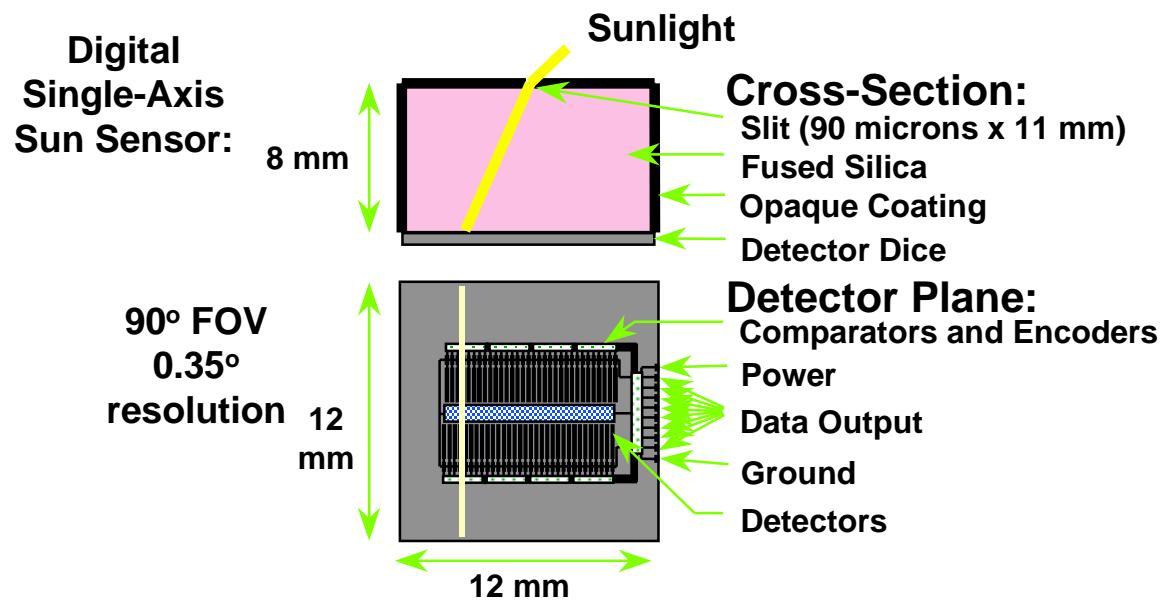


M.C. Wu, "Micromachining for Optical and Optoelectronic Systems," Proc. IEEE, Vol. 85, #11, Nov 1997; [http://www.ee.ucla.edu/
labs/laser/research/mot/1integrated.html](http://www.ee.ucla.edu/labs/laser/research/mot/1integrated.html)

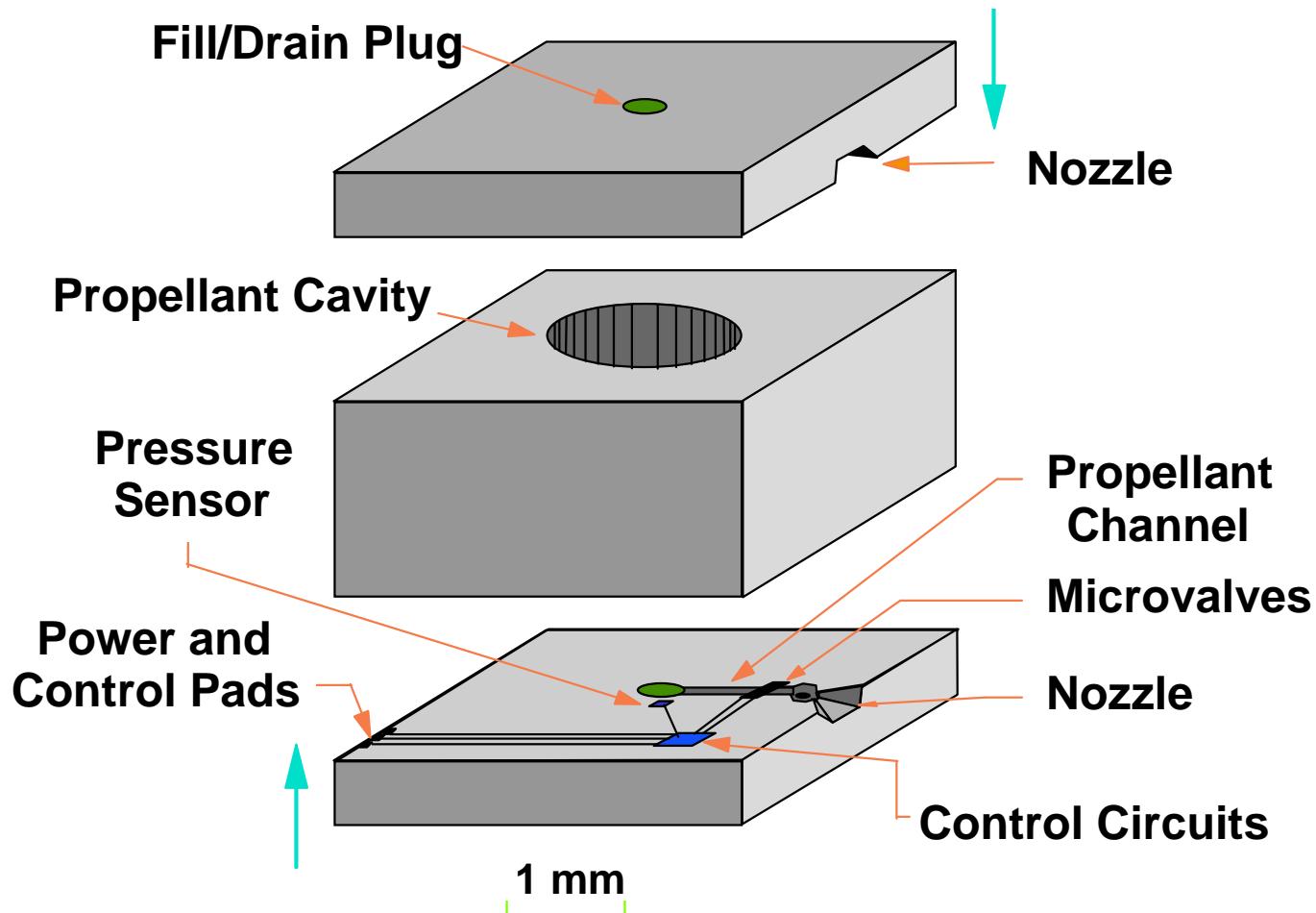
See also: "Optics & MEMS" by S.J. Walker and D.J. Nagel, <http://code6330.nrl.navy.mil/6336/moems.htm>

Single-Axis Digital Sun Sensor:

- Based on design published in ATR-95(8168)-2
“Microengineering Technology for Space Systems”
- Two prototype CMOS test chips fabricated

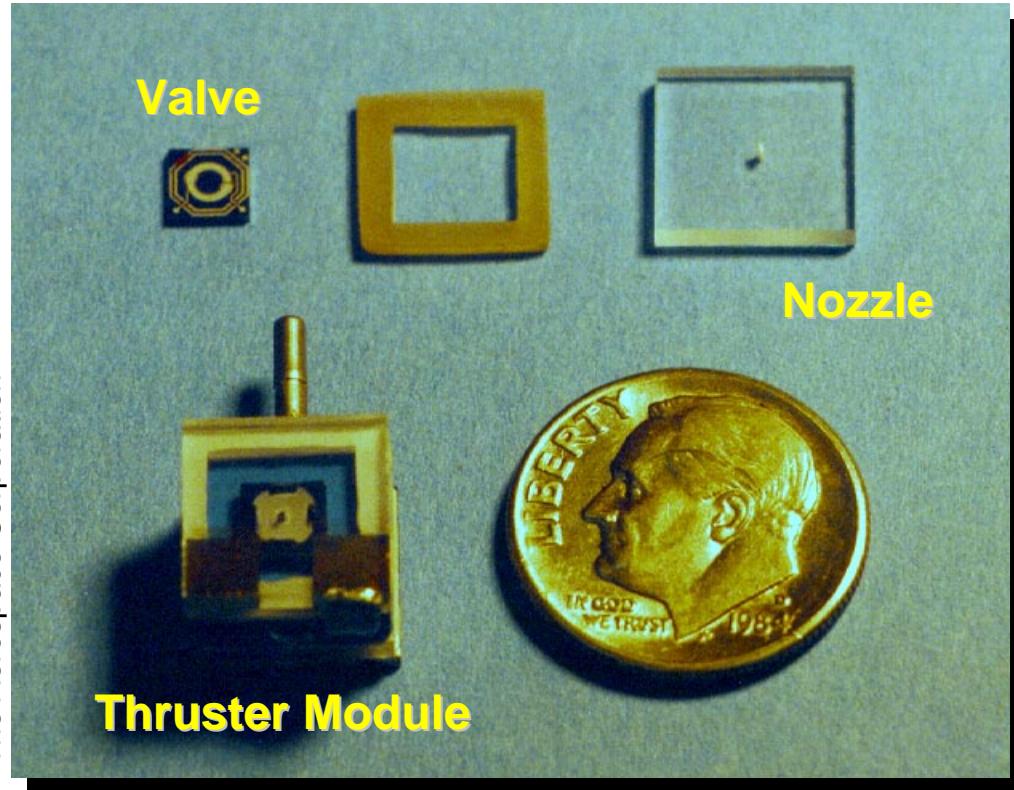


Batch-Fabricated Thruster Systems

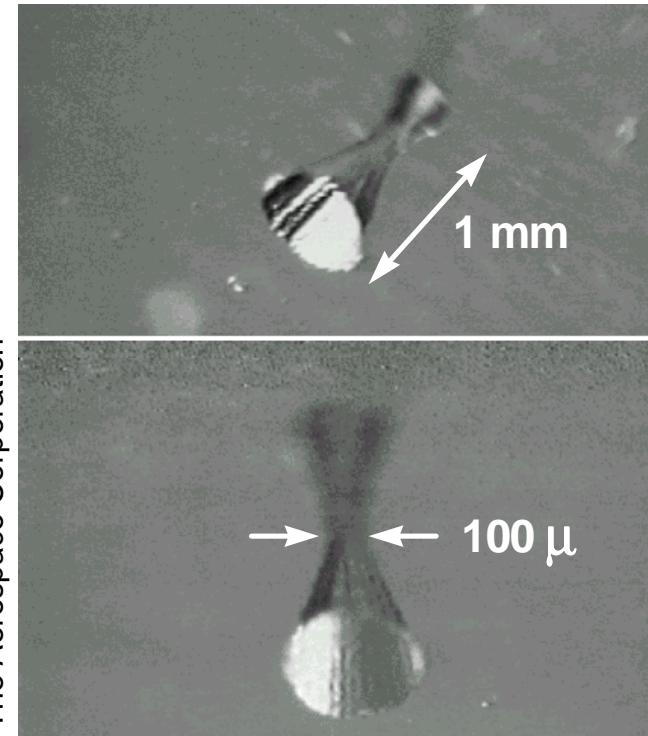


Bi-Directional Thruster Module

The Aerospace Corporation



The Aerospace Corporation

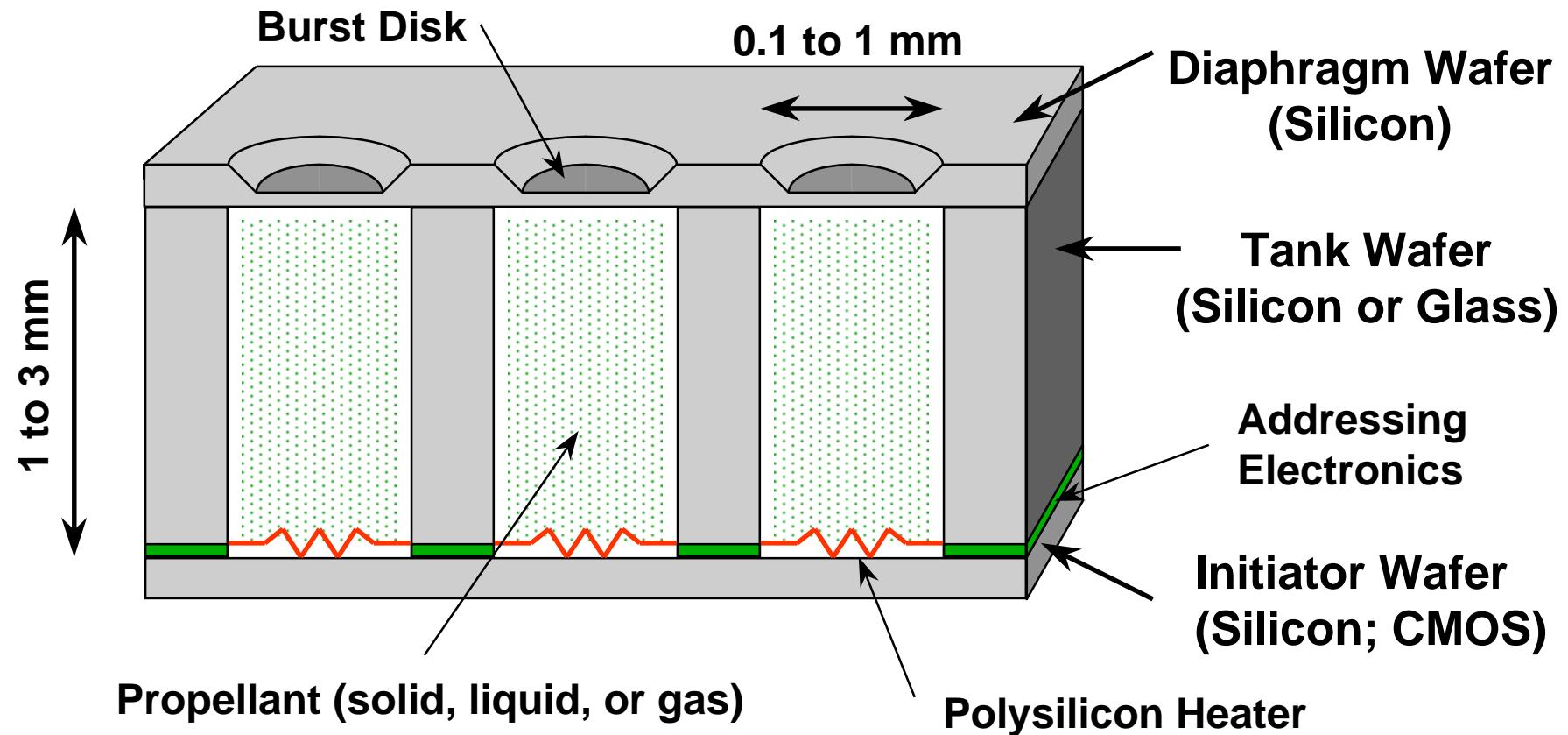


Valve = EG&G IC Sensors model 4425-15 silicon microvalve

DARPA-Sponsored Digital Micropulsion

TRW, The Aerospace Corporation, and Cal. Inst. Tech.

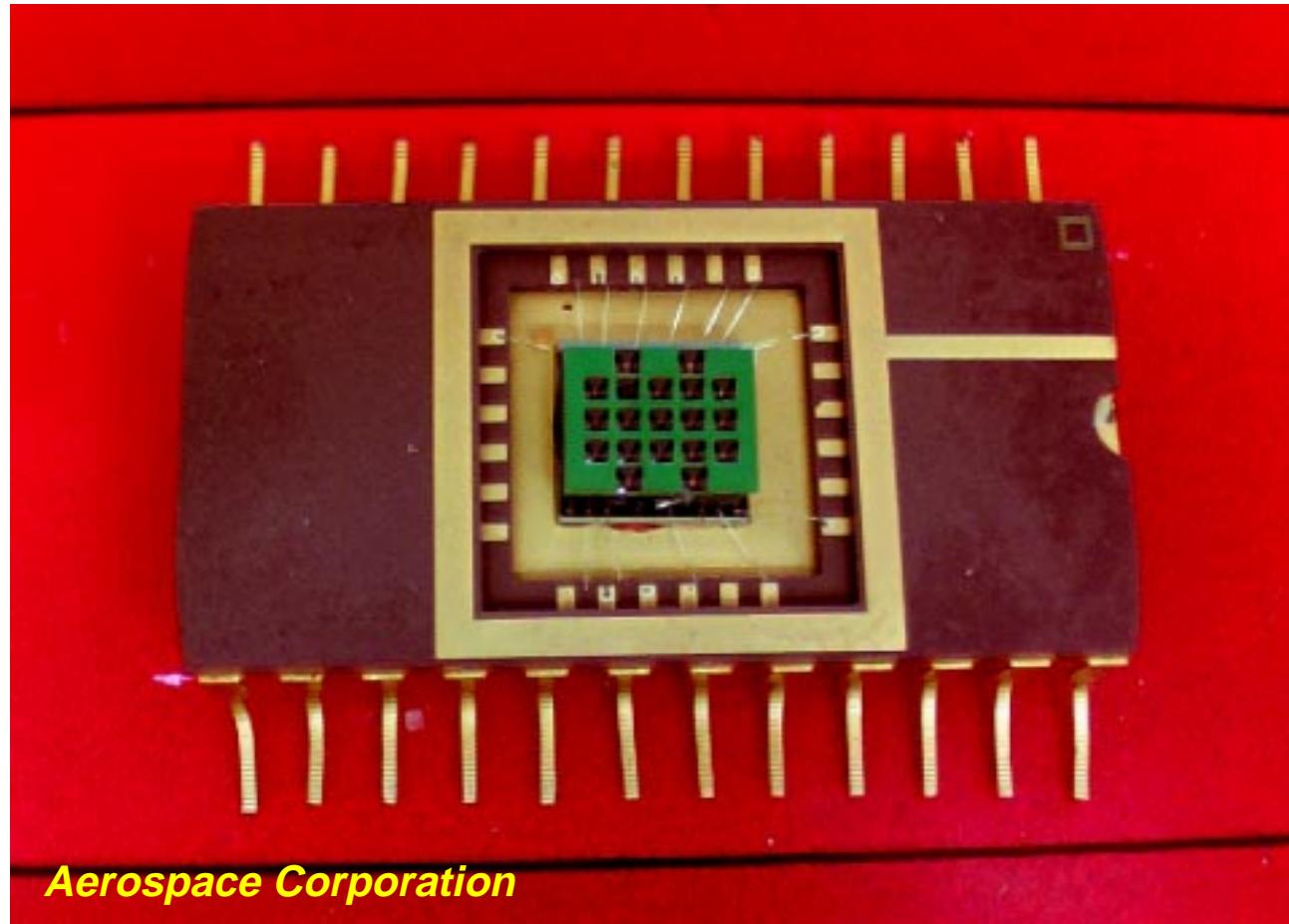
10,000 to 1,000,000 Single-Shot Thrusters on a Wafer!



Assembled “Rocket Chip”



MTO MEMS



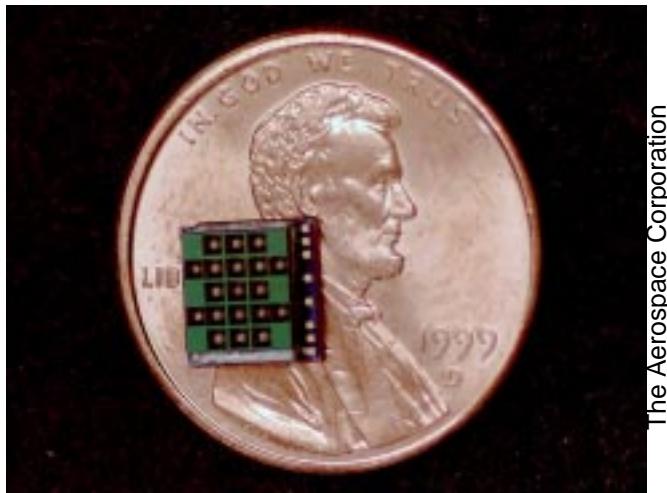
See: <http://www.design.caltech.edu/micropropulsion/index.html>

MEMS Thrusters and Components



MTO MEMS

15-Thruster “Chip” on STS-93



The Aerospace Corporation

[http://www.design.caltech.edu/
micropropulsion/index.html](http://www.design.caltech.edu/micropropulsion/index.html)

TRW, CalTech, and The Aerospace Corp.



Micro Isolation Valve

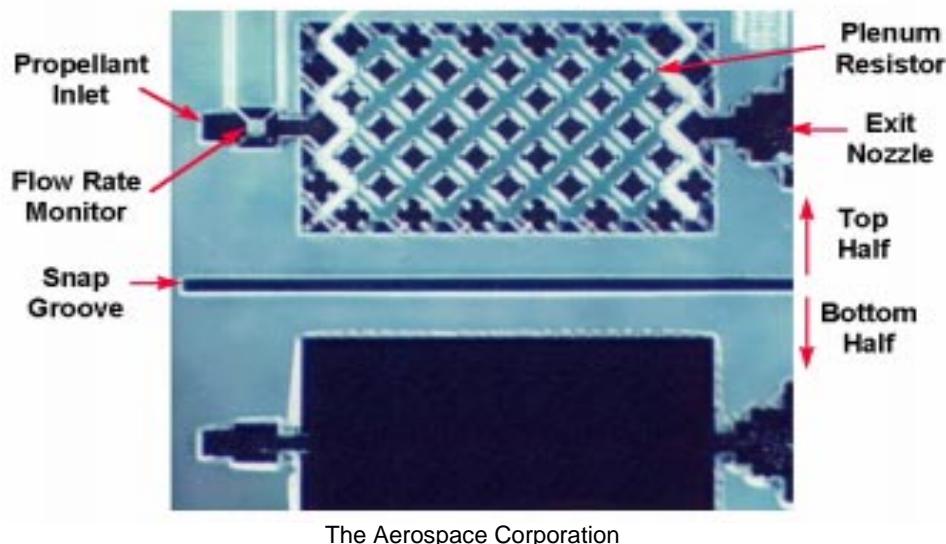


J. Mueller, S. Vago, D. Bame, D. Fitzgerald, and W. Tang, "Proof-of-Concept Demonstration of a Micro-Isolation Valve," AIAA paper 99-2726, June 1999

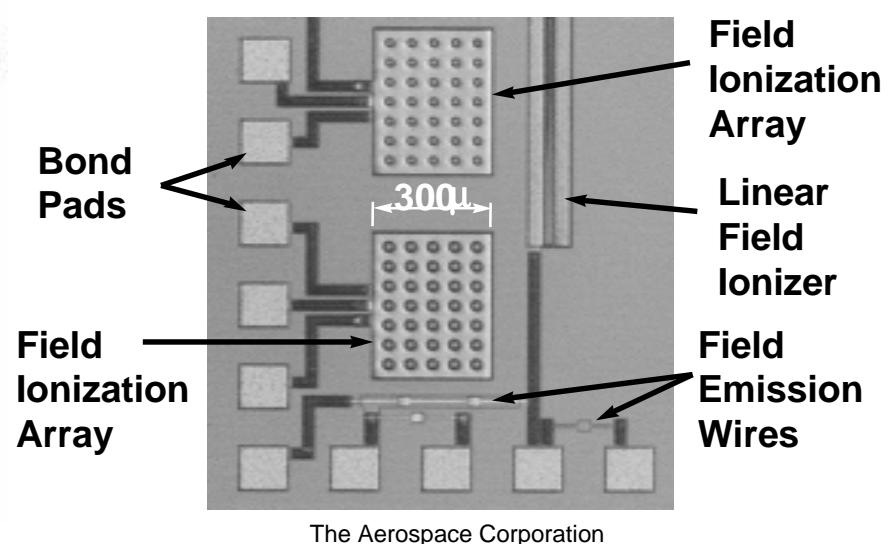
“Thrusters-on-a-Chip”; CMOS Microthrusters

- *Integrated electronics with microthrusters*
- *Sub-micron features easily available*

3-Watt Micro Resistojet:
Anisotropic etching of Si



Micro Ion Engine Test Structures:
Timed HF etching of oxide layers



MEMS Insertion Possibilities

- **Immediate:**

- Pressure sensors
- Accelerometers
- Microvalves
- Mass flow controllers
- Rate Sensors (tactical)
- Optical spectrometers
- Micro relays

- **Do it yourself:**

- Digital sun sensors
- Digital Earth sensors
- Cold Gas microthrusters
- Memtronics

- **Next year or two:**

- RF switches
- Optical switches
- Optical scanners
- Rate sensors (navigation)

WHAT DO SATELLITES DO?

- **Communications**

- Geosynchronous (GEO) and Molniya communication satellites
- Direct broadcast television
- Low Earth orbit (LEO) voice and data relay

- **Earth observation**

- Weather satellites in LEO and GEO
- Spectral mapping of surface features (LANDSAT, SPOT)
- Passive surveillance (radio through x-ray)
- Active surveillance (radar)
- Atmospheric and oceanic sounding

- **Navigation and geolocation**

- Global Positioning System and TRANSIT system in LEO
- Distress signal location

*Most Earth satellites are information and energy processors;
Can't we make "Palm Pilot" versions of spacecraft instead of main frames?*

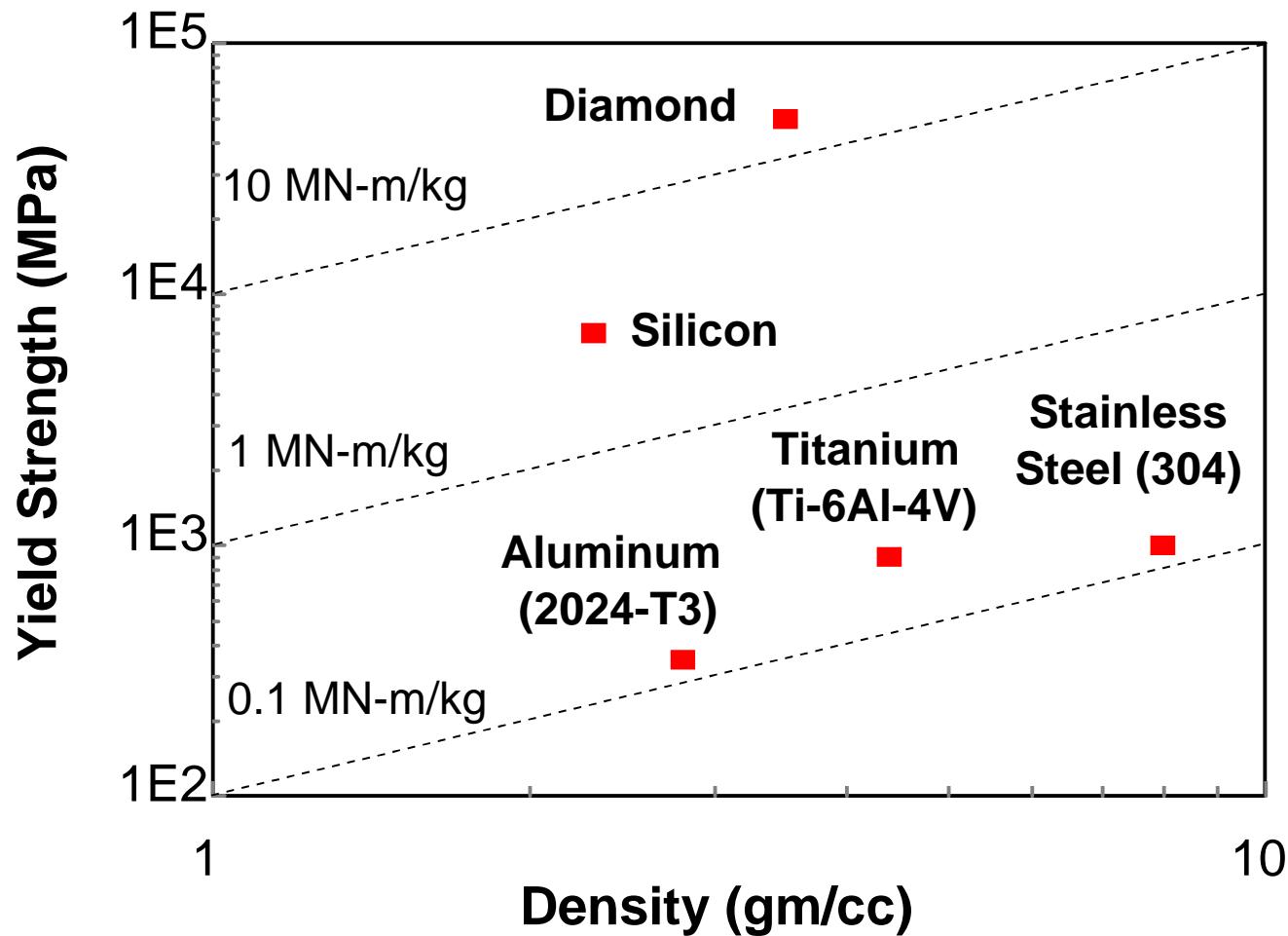
THE SILICON SATELLITE

- Current satellites contain thousands of individual components
 - Diverse materials (metals, plastics, elastomers, semiconductors, etc.)
 - Diverse manufacturing techniques
 - Multiple suppliers
 - Time-consuming assembly, inspection, and testing
- Most components are “dumb” (inert)
 - Static mechanical structures
 - Component housings, interconnects, and fasteners
 - Moving elements (momentum wheels, actuators, gyros, etc.)
- Electronic microfabrication techniques will produce smaller, smarter, and less costly components in a batch mode
 - Microelectromechanical Systems (MEMS) production has started
 - Application-specific integrated microinstruments (ASIMs) exist
 - Diverse ASIMs can be produced by a single silicon foundry

21st Century Micro/Nano/Picosatellites

- **Highly-integrated designs**
 - More functional elements, fewer piece-parts
 - Integrated diagnostics, self-test, and reconfiguration
 - “Silicon satellites”; grams-to-kilograms in mass
- **Batch or assembly-line fabrication in large lots (>100)**
 - Virtual satellites, e.g., km-scale sparse aperture arrays
 - Disposable satellites, e.g., satellite inspectors
 - Dense constellations for continuous Earth coverage
- **“Two-dimensional” satellites**
 - Large aperture/weight ratios, e.g., TechSat-21

Silicon as a Structural Material



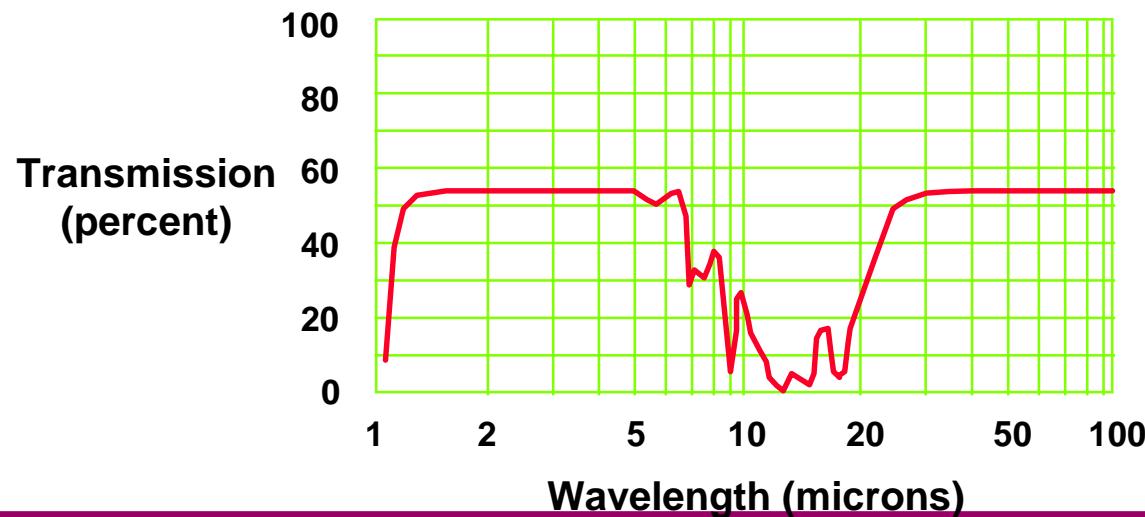
Silicon as a Thermal Control Material

Material	Thermal Conductivity (W/m-K)	Coef. of Thermal Exp. (cm/cm-K)	Melting Point (K)
Silicon (single-crystal)	150	2.5×10^{-6}	1,700
Aluminum (2024-T3)	240	2.2×10^{-5}	850
Stainless Steel (304)	16	1.7×10^{-5}	1,700
Titanium (Ti-6Al-4V)	8	9.0×10^{-6}	2,100
Diamond (single-crystal)	2,100	1.0×10^{-6}	4,200

Silicon can be thought of as a brittle metal

WHAT CAN WE DO WITH SILICON?

- It's a substrate for analog, digital, and RF circuits
- It can be a substrate for multi-chip modules
- It's a substrate for Microelectromechanical Systems
- It's mechanically strong (stronger than steel)
- It's a good thermal conductor (1/2 that of aluminum)
- It's transparent through much of the IR spectrum

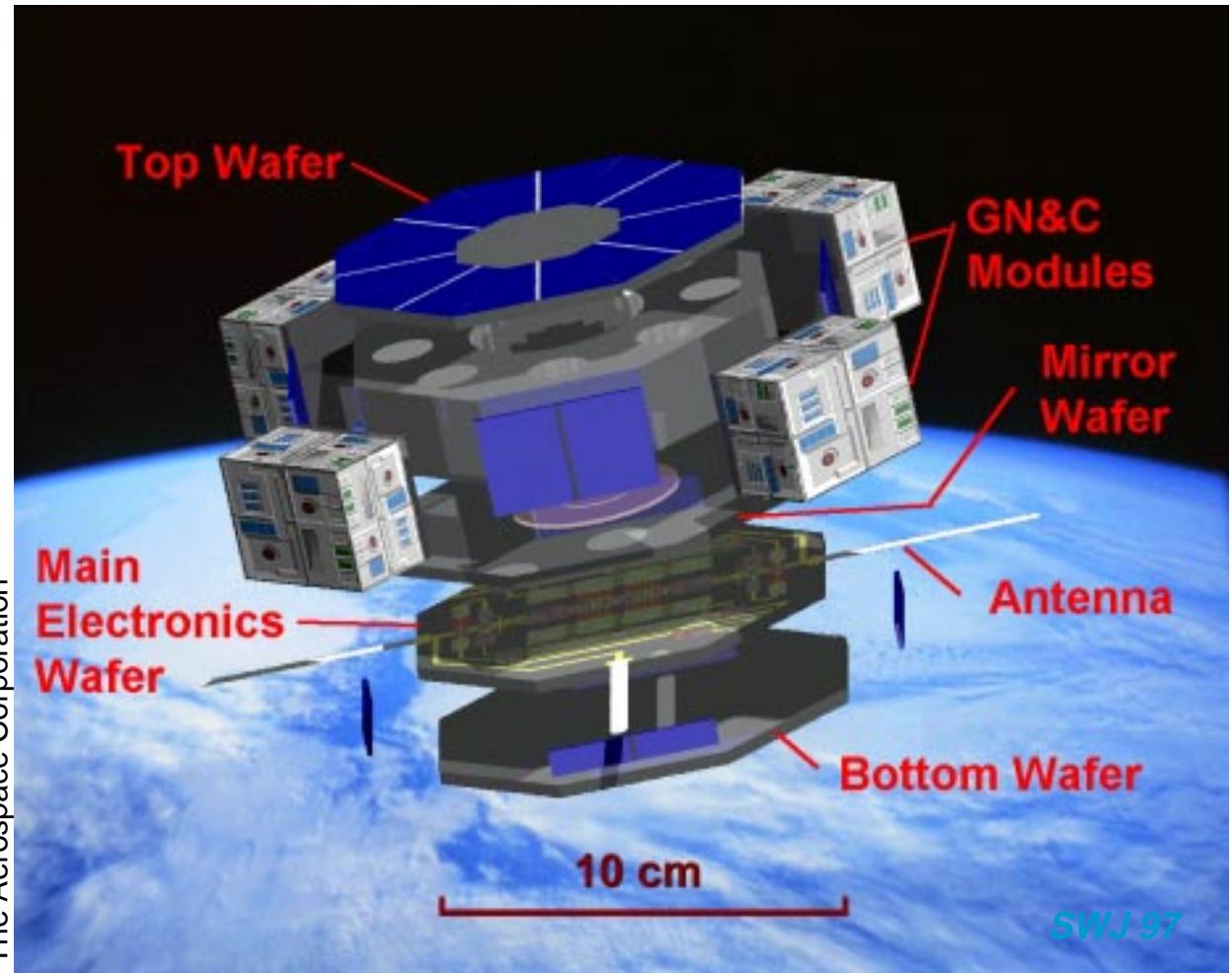


A Silicon Nanosatellite Concept

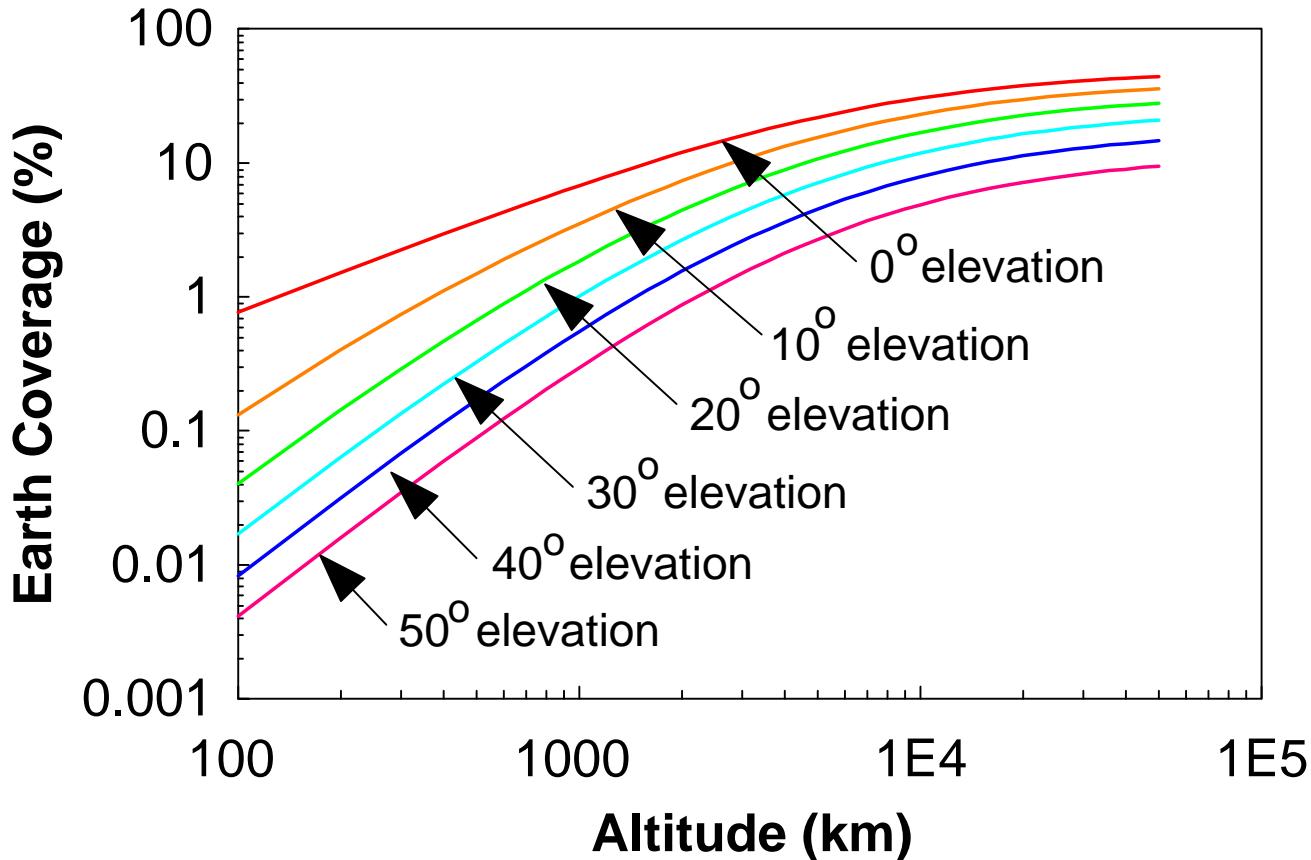
Silicon serves as:

Structure,
Radiation shield,
Thermal control,
Optical material,
MEMS substrate,
Electronic substrate

The Aerospace Corporation

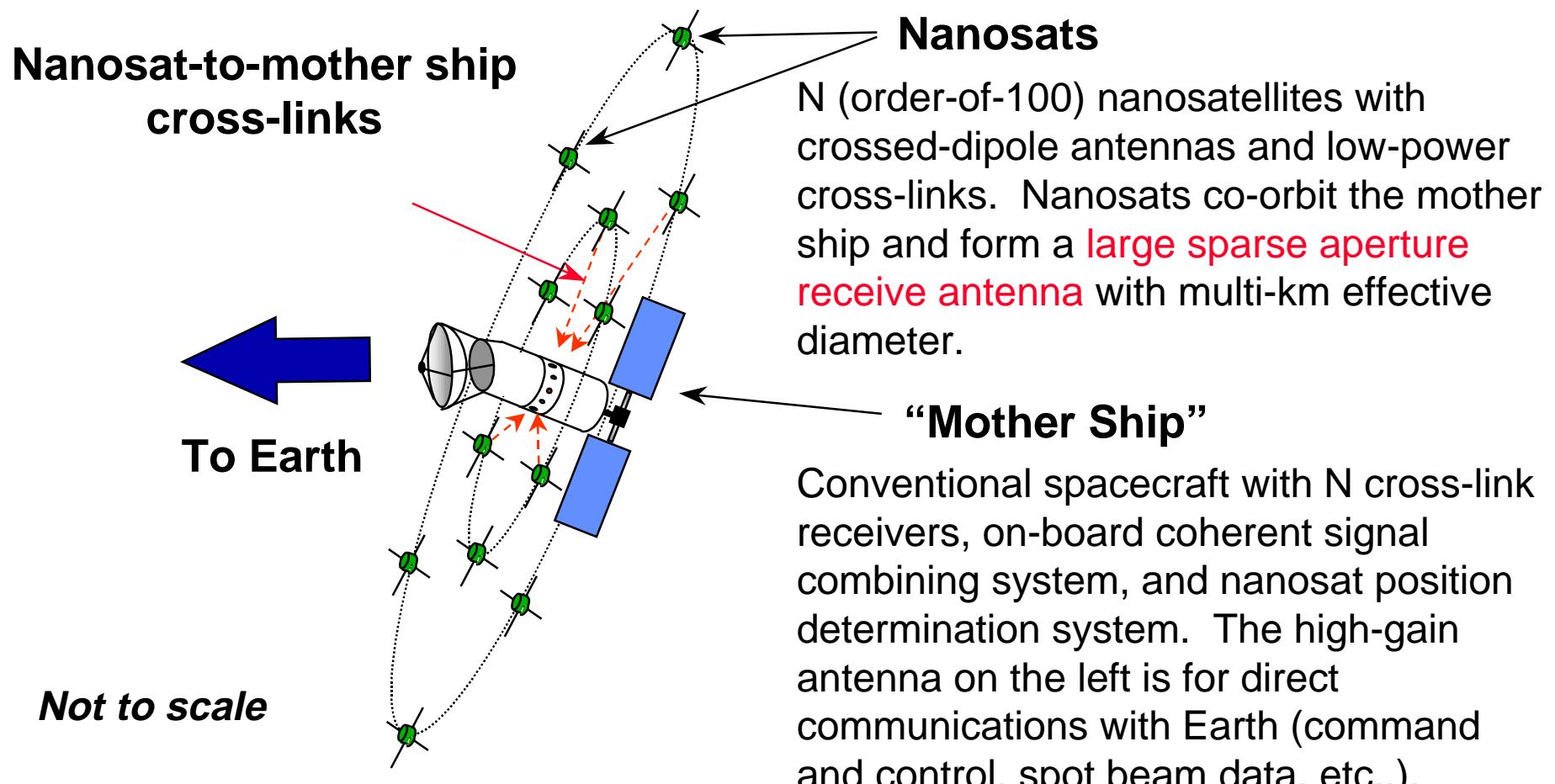


Geometric Earth Coverage for a Single Satellite



*You need several hundred satellites in LEO (<1000 km altitude)
to provide at least one satellite 40° above the horizon world-wide.*

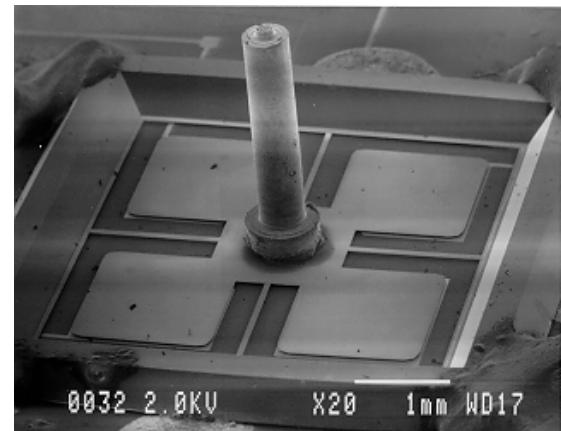
Nanosatellite Sparse Array Antenna Concept



Relevant R&D Activity (U.S.)

- **MEMS for space applications**
 - AFRL, AFOSR, DARPA
 - Sandia National Laboratories
 - NASA-JPL, NASA-Glenn
 - TRW, Draper Laboratories, Honeywell, Marotta Scientific, Hughes, Rockwell Science Center,...
 - CalTech, MIT, U.C. Berkeley, UCLA, ...
- **Integrated Micro/Nanospacecraft**
 - AFRL (TechSat-21)
 - NASA-JPL (X-2000 Deep Space Systems Technology Program)
 - Sandia (Nanosatellite)
 - NASA-Goddard (Nanosatellites for magnetospheric mapping)

NASA-JPL Microgyro



<http://csmt.jpl.nasa.gov/mgyro.html>

Summary:

- **MEMS and microtechnology can enable small, lightweight, but sophisticated spacecraft for challenging missions**
- **Mass-produced, integrated spacecraft can enable new space missions**
- **Spacecraft design and space architectures may radically change during the next decade**